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Loss Estimation: A Load Factor Method

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Abstract— **This paper focuses on Power Loss estimation in Electrical Sub Transmission and Distribution systems. The earliest empirical approaches were by Buller and Woodrow in 1928, Hoebel in 1959, M.W. Gustafson from 1983 to 1993. Gustafson changed the values of the coefficients and provided them with a constant loss term. It has been observed that this approach is not suitable for the present load scenario. In this paper, its successive approach has been proposed and tested with real time data. It has been concluded that the relationship between loss factor and load factor is not as complicated as perceived but easily understandable. By using exponential curve fitting, a relationship that is very close to reality can be obtained. To verify the obtained equation, data has been collected from a 33kV sub transmission line existing between 132kV/33kV Thurkayamjal substation and 33kV/11kV Hayathnagar substation, APTRANSCO, Andhra Pradesh.**

Index Terms— **Load factor, Loss factor, Load curve, Loss curve, exponential curve fitting, Sub Transmission and Distribution.**

I. Introduction

According to the fundamental laws of nature, energy cannot be converted from one form to the other, unless until there is an opposition to the conversion. An analogous statement exists for Electric Power Transmission and Distribution. According to this statement, power cannot be transmitted from one port to the other, without losses. They arise as power flows, to satisfy consumer demands through the network. Electrical energy is converted from various forms of conventional and non conventional energy sources at suitable locations, transmitted at a high voltage over long distance and distributed to the consumers at a medium or low voltage. A distribution system consists of a substantial number of distribution transformers, feeders, and laterals, due to a large number of consumers spread over a wide geographical area. Some of the input energy is dissipated in the conductors and transformers along the delivery route. Losses increase the operating cost, estimated to add 10% to the cost of electricity and also approximately 25% to the cost of delivery. These costs are levied on the consumers.

Studies have indicated that losses in a distribution system contribute to a major part of losses in a power system (approximately about 70% of total losses). Therefore, the distribution system loss has become more and more of concern, because of the growth of load demand and the wide area it covers. It is important to estimate them accurately in order to take appropriate measures for reducing the losses. The evaluation and reduction of energy losses present the distribution companies with taxing challenges. The accurate estimation of electrical losses enables the supply authority to determine the operating costs, with greater accuracy, and abate the dissipation of power.

Total system loss is the difference between the energy sent and the energy received by the end users. Distribution system losses are of two types:

- Technical losses, which arise due to the current passing through the network components, i.e. the conductors, coils and the excitation of the windings of the transformers and others.
- Non-Technical Losses are those ones that cannot be calculated beforehand. For e.g. problems with metering, billing or collection systems, and the consumers pilfering power.

The loss factor can be used to calculate energy losses for those parts of the electric system where the current flowing is proportional to system load each hour, which would typically be the distribution and sub transmission systems. Attempting to make a lead in this aspect in 1928, Buller and Woodrow proposed a relationship between load factor and loss factor, by using a completely empirical approach [1]. This approach was used by Hoebel in 1959 [2]. Hoebel asserted that “A number of typical load curves experienced on a large system have been studied to determine this relationship”. Martin. W. Gustafson, a Transmission/ Substation design engineer, modified the existing relationship between the two factors [3]. He modified the constant coefficient and also added a new coefficient for losses [4], [5]. Later on various methodologies were proposed to estimate sub transmission and distribution losses [8]. Simplified models of distribution feeder components for load flow calculations are proposed in [9]. An approximate loss formula based on the load-flow model is proposed in [10].Simulation of distribution feeders with load data estimated from typical customer load patterns is presented in [11]. Closed-form formulas for computation of losses using a three phase load-flow model are proposed in [12]. Loss formulas based on fuzzy-c-number (FCN) clustering of losses and cluster-wise fuzzy regression techniques are presented in [13]. A hybrid top/down and bottom/up approach is applied to estimate losses in [14]. A new approach has being proposed for nontechnical loss analysis for utilities using the modern computational technique extreme learning machine [15]. Difficulty in obtaining accurate data has a significant impact on the accuracy of their results.

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Mathematics provides us curve fitting methods to establish the exact relationship between two sets of data. The basic approaches like that of Buller and Woodrow utilized curve fitting, to find the relationship. In any relationship between loss factor and load factor, providing fixed limits to the values of the coefficients is important, as this helps in judging if the values of the coefficients obtained are right or not. Before discussing the new approach to estimate energy losses by using mathematical methods, it is important to understand the basic approach i.e., Buller & Woodrow Equation. By using all the following approaches, the loss factor of a system can be approximated. But, the loss factor of a system does not give us any information of the performance of the system. We must use the basic loss factor definition to calculate the average losses of the system.

II. Basic Approaches

In 1928, F.H. Buller and C.A. Woodrow, two engineers with the General Electric Company, developed an empirical equation (4) between Loss factor and Load factor [l]. Buller and Woodrow assumed an arbitrary and idealized case of a load curve, where it consisted of a peak load for a time t, and an off-peak load for a time (T-t), where T was the complete time period taken into account as shown in Fig. 1 [7]. As the loss varies with square of the current, the loss varies with the square of the load. Therefore, the loss curve too is in the same shape as that of the load curve. The *load curve* is a plot of *load* variation as a function of time for a *definite* group of end-users. Similarly, the *loss curve* is a plot of *loss* variation as a function of time. Load Factor (LD_f) is defined as the ratio of average load to the peak load over a designated period of time. Loss Factor (LS_f) is defined as the ratio of average loss to the peak loss over a designated period of time.

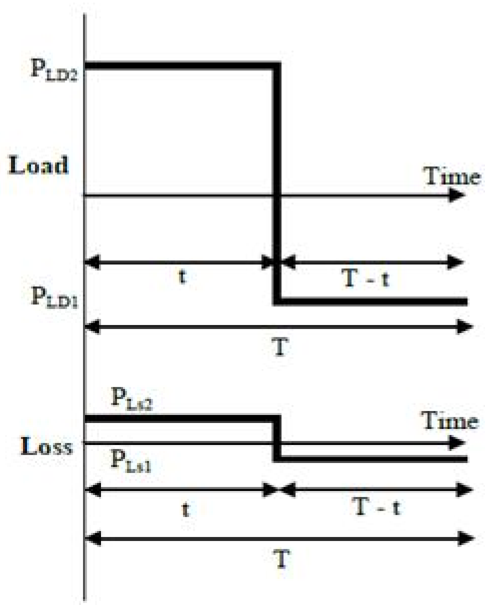

Figure 1. Load Curve and Loss Curve

$$LD_f = t/T + (P_{LD\,2}/P_{LD\,1})(1 - t/T) \quad (1)$$

$$EQ_f = t/T + (P_{LS\,2}/P_{LS\,1})(1 - t/T) \quad (2)$$

As loss varies with the square of the load,

$$LS_f = t/T + (P_{LD\,2}/P_{LD\,1})^2(1 - t/T) \quad (3)$$

Buller and Woodrow correctly believed that the relationship of load factor and loss factor on an actual electric system should fall between the two boundary conditions viz. complete peak (t'!T) and complete off-peak (t'!0) . They plotted these two extremities and applied curve fitting for the area within the two curves, to get the relationship between the two factors as shown in the Fig. 2. This work led them to the development of equation (4) with a constant coefficient of 0.3**.** The constant coefficient was derived from representative load curves based on the available data and limited computing capability in 1928.

$$LS_f = (LD_f)^2(1\text{-}X) + (LD_f)X \quad (4)$$

Where, LS_f = Loss Factor
LD_f = Load Factor
X = Constant Coefficient

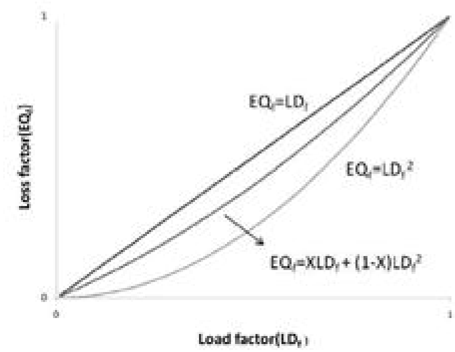

Figure 2. Loss Factor versus Load Factor

Even though, Buller and Woodrow's approach was considered to be useful, and it has been used, it consists of approximations far from reality. The load curve considered was an ideal one consisting of only peak and off peak as shown in Fig 1. The average is a function of only peak and off peak. But the intermediate values affect the average. In equation (3) it was considered that

$$P_{LSk} = C_k P_{LDk} \; [k=1,2,3\ldots]$$

With an assumption $C_1 = C_2$. This need not be right, as the value of the coefficient can be different at the off-peak, than at the peak.

H. F. Hoebel used the original equation (4) and also developed equation (5) in terms of loss factor and load factor with an exponential coefficient [2]. The value for the exponent commonly used in practice was 1.6.

$$\textit{Loss Factor} = (\textit{Load Factor})^{1.6} \quad (5)$$

Martin. W. Gustafson developed a quadratic equation to determine sub transmission and distribution system losses [3]. He also observed that the values of 0.3 for the constant coefficient and 1.6 for the exponential coefficient, no longer appear to be appropriate and revised the coefficients as 0.08 for the constant coefficient and 1.912 for the exponent [4]. A constant term is added which represents no load losses [5]. He extended the same approach to determine transmission

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system losses with special considerations [6].

III. Proposed Mathematical Approach

Many processes in nature have exponentia1 dependencies. The advantage of exponential equations is that with the right values of coefficients, any curve can be approximated in the form of an exponential equation i.e., within the limits of the given data. In exponential curve fitting, any function is approximated as

$$y = Ae^{Bx} \tag{6}$$

The advantage of such an equation is that 'A' decides the 'y' intercept of the curve, and 'B' gives the function its curvature. Taking the logarithm of both sides of (6)

$$Log\ y = Log\ A + Bx \tag{7}$$

Then, the best fit-values are

$$A = \frac{\sum_{i=1}^{n} \ln y_i \sum_{i=12}^{n} x_i^2 - \sum_{i=1}^{n} x_i \ln y_i}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \tag{8}$$

$$B = \frac{n\sum_{i=1}^{n} x_i \ln y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} \ln y_i}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \tag{9}$$

Where 'x_i' and 'y_i' are the sets of data, which must be fit in the required curve. Using (6) to fit a curve between the two factors.

Let the relationship between them be

$$LS_f = ae^{bLD_f} \tag{10}$$

Taking the natural logarithm on both sides of (10)

$$ln(LS_f) = ln(a) + bLD_f \tag{11}$$

This can be plotted as a straight line between the natural logarithm of loss factor and load factor. Therefore, the general equation of the relationship can be shown

$$ln(LS_f) = A + B\,(LD_f) \tag{12}$$

The values of these coefficients can be determined by using (8) and (9). Due to its desired features of a given 'y' intercept value, and curvature, it can be used easily to estimate the loss factor of a system, from a given value of a load factor.

IV. Results

The proposed approach was tested on a 33kV sub transmission line existing between 132kV/33kV Thurkayamjal substation and 33kV/11kV Hayathnagar substation, APTRANSCO, Hyderabad, Andhra Pradesh. The annual load and loss data of the test system was collected for one year and the monthly load and loss factors were evaluated by plotting the monthly load and loss curves. The monthly Load Curves and Loss curves are shown in Fig. 3 and Fig. 4.

The constant coefficient 'X' of Buller and Woodrow (1) has been calculated from the average values of monthly load and loss factors. Calculated value of the coefficient 'X' was 0.6432**.** It is further used to calculate the loss factors from respective monthly load factors. The coefficients of the proposed approach 'A' and 'B' were calculated from the average monthly load and loss factors. The calculated value of the coefficients A and B were **-**2.2073 and 2.231**.** They are further used to calculate the loss factors from the respective monthly load factors. The summary of the analysis is shown in Table 1. From the results, it can be seen that the method presented is a new tool capable of estimating sub-transmission and distribution system losses with greater accuracy, than what was previously available. It is also observed that the values of the coefficients are very important in estimating losses, but they cannot be generalized for any system. This is due to the fact that each system has a different load profile, which leads to different values of coefficients. Hence, it is advised that a distribution company, use previous data, to calculate the values of the coefficients, for their respective load profiles. Fitting an exponential curve to data does not need any tedious programming or simulation.

V. Calculation of losses from the load factor

Using the above mentioned method, we calculated the loss factor of a system, at a particular instant. The loss at that time can be estimated by using the basic definition of loss factor, viz.

$$LS_f = \frac{AverageLoss}{PeakLoss}$$

Therefore,

$$AverageLoss = LS_f \times PeakLoss$$

But, using the above mentioned approach, the loss factor was estimated as

$LS_f = ae^{bLDf}$

Hence,

$$AverageLoss = \left(ae^{bLD_f}\right) \times (PeakLoss)$$

Most of the electrical systems have constant values of their peak losses. This value of the peak loss can be taken from the data is collected regularly, by the distribution company. Therefore,

$$AverageLoss = Pe^{bLD_f}$$

Where, $P = a \times PeakLoss$

This relationship was used to calculate the average losses of the system from which data was collected. The results are shown in Table. II.

Conclusions

Buller and Woodrow were right, but their approach contained too many assumptions to be considered to be close to the original value. Hoebel relationship had the capacity to get a curvature close to the original curve, but it ignored constant losses. Every relationship between two sets of data can be expressed in terms of infinite powers of the 'x' coeffi

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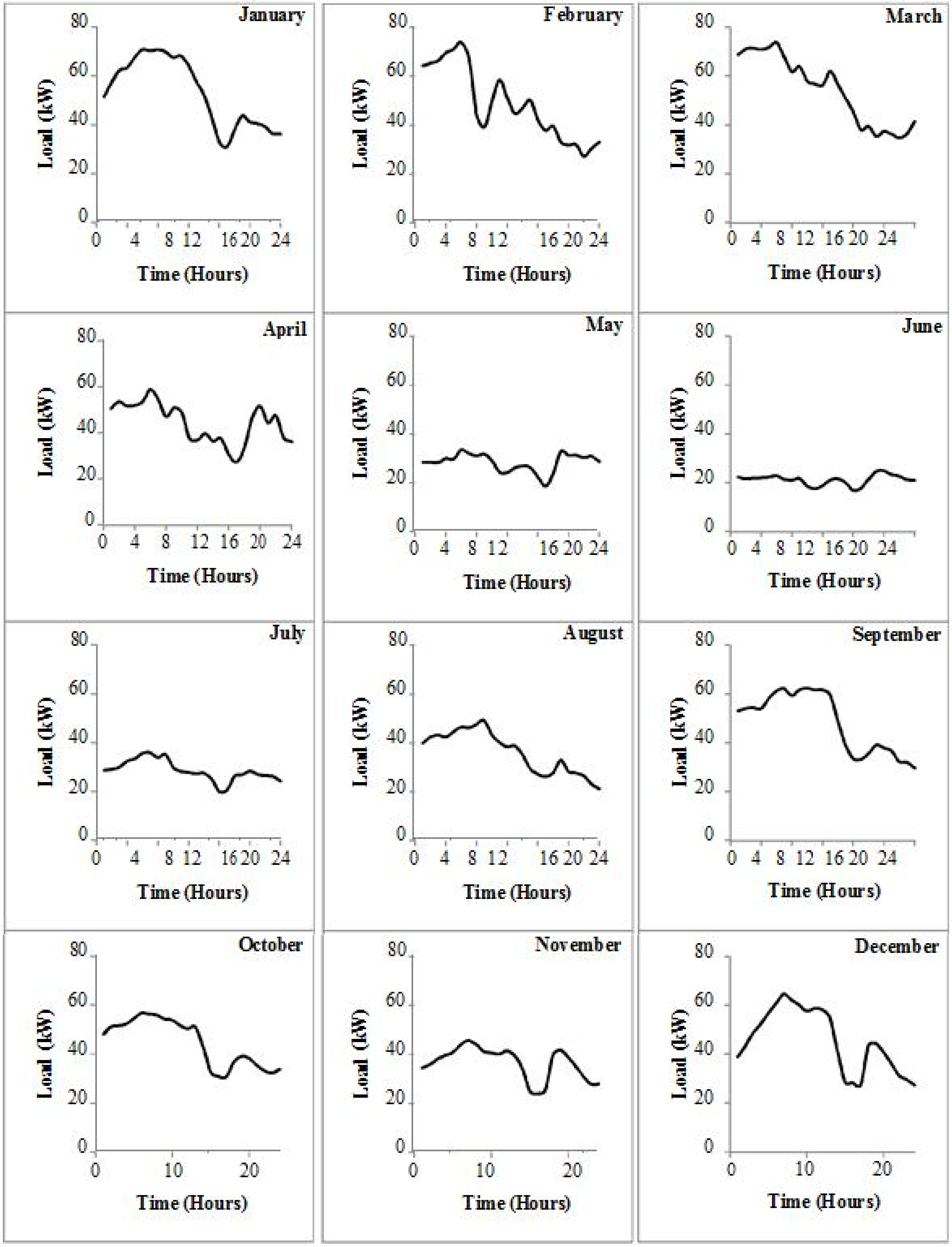

Figure 3. Monthly Load Curves

cient. Martin. W. Gustafson made use of this polynomial, but utilized only a second order equation. This was the source of error. The new approach can be considered to be very close to the original relationship, because it considers all the terms in the polynomial expansion (in the expansion of e^x) including a constant term which represents total constant losses due to large number of Distribution Transformers in the Electrical Distribution System.

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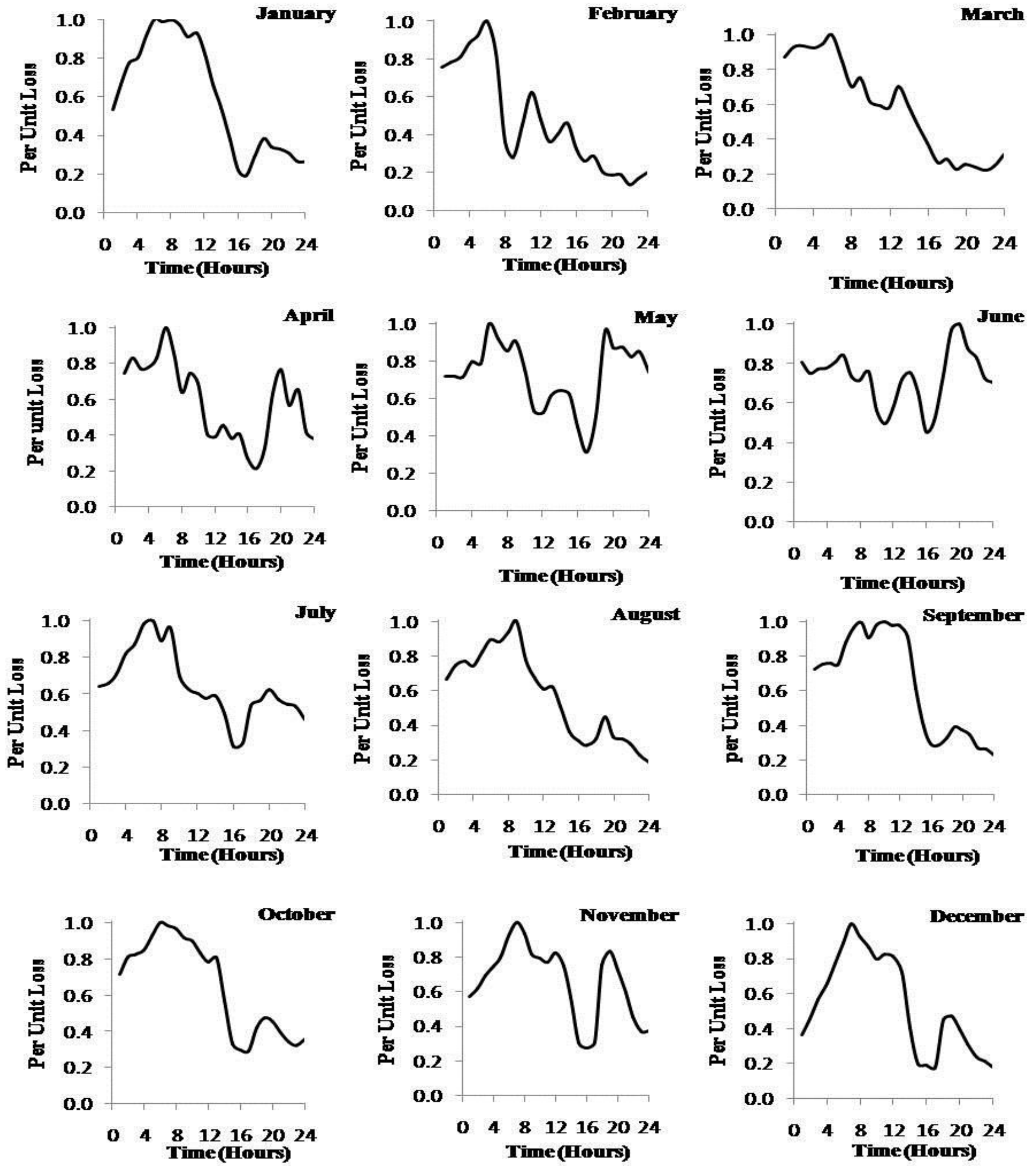

Figure 4. Monthly Loss Curves

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TABLE 1. COMPARISON OF LOSS FACTORS

Month	Actual Values		Loss Factors Compared			
	Load Factor	Loss Factor	Buller & Woodrow	Hoebel	Gustafson	Proposed Approach
January	0.7515	0.6026	0.6849	0.6331	0.6575	0.5882
February	0.6598	0.4740	0.5797	0.5141	0.5286	0.4794
March	0.7380	0.5793	0.6690	0.6149	0.6382	0.5707
April	0.7547	0.5898	0.6886	0.6373	0.6620	0.5924
May	0.8480	0.7305	0.8020	0.7680	0.7969	0.7294
June	0.8516	0.7310	0.8065	0.7733	0.8023	0.7354
July	0.7973	0.6490	0.7396	0.6959	0.7231	0.6514
August	0.7360	0.5718	0.6667	0.6124	0.6355	0.5683
September	0.7763	0.6398	0.7144	0.6669	0.6930	0.6217
October	0.7881	0.6485	0.7285	0.6831	0.7098	0.6382
November	0.7996	0.6580	0.7424	0.6991	0.7265	0.6584
December	0.7063	0.5361	0.6323	0.5733	0.5935	0.5318

TABLE II. COMPARISON OF ACTUAL AND CALCULATED LOSS

Month	Actual Average Loss (kW)	Calculated Average Loss (kW)
January	0.301916667	0.294711337
February	0.310958333	0.314474906
March	0.378291667	0.372668149
April	0.307291667	0.30862299
May	0.213291667	0.212992855
June	0.16375000	0.164727617
July	0.210291667	0.211061349
August	0.24987500	0.248328492
September	0.348708333	0.338830648
October	0.31387500	0.308884592
November	0.260583333	0.259301105
December	0.29112500	0.288784375

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